ENVIRONMENTAL FACTORS DETERMINING THE YIELD AND QUALITY OF WINTER WHEAT IN SASKATCHEWAN

M.H. Entz and D.B. Fowler
Crop Development Centre
University of Saskatchewan

ABSTRACT

Effects of prevailing environmental conditions, N fertilization and crop cultivar on winter wheat productivity were investigated independently in field experiments in Saskatchewan between 1984 and 1986. The relationship between grain yield and grain protein with weather and soil water parameters indicated that "critical" stress periods exist for these parameters. The critical stress period for grain and protein yield was found to occur between June 9 and June 24 while environmental conditions both before and after anthesis were critical for grain protein content. Evaporation during the two weeks before heading followed by root zone available water at anthesis and precipitation were the most important environmental factors. Addition of N fertilizer increased crop growth, rate of water use and water use efficiency. Despite the higher tiller mortality and lower amount of available soil water after anthesis associated with high N levels, N additions significantly increased grain yield. In dry environments, the tall cultivar 'Norstar' significantly outyielded the semi-dwarf 'Norwin'. The superior performance of Norstar under high stress conditions was attributed to its higher growth rate, especially before anthesis. In wet environments, Norwin outyielded Norstar and the superior performance of the semi-dwarf under these conditions was attributed to a greater harvest index and better water economy.

INTRODUCTION

No-till winter wheat is an important dryland crop in Saskatchewan and holds much promise in extending crop rotations and soil conservation. It is well accepted that a major limiting factor to cereals grown in the Canadian prairies is a shortage of moisture (Lehane and Staple, 1965; Robertson, 1974), however, information regarding the relationship between the crop water environment and winter wheat productivity is lacking.

The extent that moisture and temperature stresses reduce the yield of wheat is dependent upon growth stage and pre-stress conditioning. It is generally accepted that the influence of high temperature and water stress on the yield of wheat is smallest during the tillering stage and greatest during the period between stem elongation and anthesis (Nix and Fitzpatrick, 1969; Day and Intalap, 1970; Fischer, 1973; Fischer and Maurer, 1976; Doorenbos and Kassam, 1979; Johnson and Kanemasu, 1982). However, it has been demonstrated that the sensitivity of the critical booting/heading period to water stress can be reduced when the crop is pre-stressed (Singh, 1981). Observations such as this emphasize the importance of considering environmental conditions for the entire growing season when attempting to assess the influence of critical stress periods on crop productivity in different regions of the world.

Presented at the 1988 Soils and Crops Workshop

The effects of moisture availability on the inverse yield-protein relationship in wheat has been documented by Terman et al. (1969). Protein content of winter wheat has been reported (Smika and Greb, 1973) to be negatively correlated with precipitation received 40 to 55 days prior to maturity and with available soil water in the 1.2 to 1.8 meter depth at seeding time. Soil water stresses at flowering have also been shown to influence grain protein of 'Neepawa' spring wheat (Dubetz and Bole, 1973).

The importance of available soil nitrogen in determining grain yield is well documented (Brown, 1971; Fowler et al., 1987) and crop response to added N is greatly influenced by the prevailing crop water environment (Henry et al., 1987). Nitrogen fertilization usually results in greater soil water use during the first part of the season (Fischer and Kohn, 1966) leading to increased risk of post-anthesis water shortages. However, Viets (1966) concluded that risk associated with N fertilization under water-limiting conditions has been overstated and that N fertilization is very important in maximizing water use efficiency.

Cultivar selection based on the type of crop water environment expected has been suggested in the literature. Semi-dwarf wheat cultivars were shown by Laing and Fischer (1977) to generally better adapted to all conditions while Briggle and Vogel (1968) found semi-dwarf wheats least adapted to low productivity environments. Semi-dwarf winter wheat cultivars have recently beem introduced in Saskatchewan and a better understanding of the adaptation of both traditional tall cultivars and semi-dwarfs is necessary.

The objective of this paper is therefore to determine the critical environmental stress periods associated with winter wheat production in Saskatchewan and to assess the effects of N and cultivar type upon the yield-crop water environment relationship.

MATERIALS AND METHODS

Field experiments were conducted in central Saskatchewan at Saskatoon and Clair in 1984, Saskatoon, Clair, Outlook Perdue and Kamsack in 1985 and Saskatoon,Clair, Outlook and Watrous in 1986. Weather stations equipped with microloggers were located at all sites except two. Weather data for these sites was collected from nearby Environment Canada meteorological stations. Daily values for minimum and maximum air (screen) temperatures and rainfall were recorded and growing degree days were calculated using a base temperature of 5C. Evaporation was recorded daily from a Class A pan at the nearest Environment Canada weather station (furthest distance 50 km).

Environmental stress periods - 'Norstar' winter wheat was direct seeded into standing stubble in late August or early September at a seeding rate of 75 kg ha^{-1}. Plot size varied among sites and ranged from 10 to 15 m^2. Thirty kg ha^{-1} P_2O_5 (11-51-0) was applied with the seed. Ammonium nitrate (34-0-0) fertilizer was broadcast in the early spring at a rate of 100 kg ha^{-1}.

Soil water to 130 cm (100 cm at Clair in 1984) was measured over the period from mid-May to harvest using a neutron probe (Troxler laboratories). Surface soil moisture (0-10 cm) was determined gravimetrically. Soil water availability for individual soil depth increments (0-10, 10-30, 30-50, 50-70, 70-90, 90-110, and 110-130 cm) was expressed as extractable water, which is the difference between the highest (after drainage) and the lowest measured volumetric water content (Ritchie, 1983). Rooting zone of the crop was defined as the zone in which significant ($P \leq 0.05$) soil water depletion occurred between sampling dates (approximately every two weeks). This technique has been previously verified by comparing direct root observations (Entz et al., 1987) with soil water use data (r^2=0.88**). This method can only estimate rooting depth to the nearest 20 cm, i.e., an individual soil depth increment.

Atmospheric moisture parameter measurements were divided into six 15-day growth stages (GS) beginning 45 days prior to anthesis and extending 45 days after anthesis. Extractable soil water in the rooting zone and in the entire soil profile was determined for three different time periods; early June at the beginning of elongation (E), the end of June (average date-June 24) at anthesis (A), and the soft dough stage (GF).

Relationships among variables measured were evaluated for linearity and simple correlations were utilized to determine the closeness of the relationships. Forward stepwise regression analyses were used to identify environmental variables with the largest influence on agronomic characters. Independent variables that significantly ($P \leq 0.05$) reduced the residual variance of the dependent variables were considered to provide additional information on the dependent variable. Measurements of agronomic characters employed in correlation and regression analyses were average values for all replications at each site for each year.

Nitrogen effects -The influence of N fertilization (spring applied ammonium nitrate at 0,33,67 and 100 kg/ha on Norstar winter wheat was investigated at 7 locations between 1984 and 1986. At each of these locations, 2 moisture regimes were compared; dryland vs. limited irrigation (irrigation to approximately 130% of normal growing season precipitation). Dry matter accumulation was measured at anthesis and maturity. Crop water use (seasonal soil water use plus precipitation and irrigation) and water use efficiency (kg/ha/mm crop water use) were calculated.

Genotypic effect - The tall cultivar Norstar was compared with the semi-dwarf cultivar 'Norwin'at 6 dryland locations between 1984 and 1986. Dry matter accumulation, crop water use, water use efficiency (WUE),grain yield and harvest index (HI) were measured.

RESULTS AND DISCUSSION

1. Critical environmental stress periods affecting yield and protein of Norstar winter wheat in Saskatchewan.

The average grain yield over the 11 locations was 2,755 kg/ha (range form 1376 to 5003 kg/ha) while the average grain protein content was 13.4% (Range from 10.6% to 16.2%). Protein yield averaged 354.1 kg/ha and ranged from 203.9 to 640.3 kg/ha. The average weather pattern encountered in these studies show evaporative demand (E) to be lowest for growth stage (GS) 1 and greatest for GS4. A similar trend was observed for growing degree days (GDD). These patterns are typical of the long-term climatic conditions experienced in Saskatchewan (Fowler and Entz, 1986). Precipitation (P) was evenly distributed over the growing season and the average growing season rainfall (17 cm) for these trials was close to the long-term average of approximately 16 cm. The average amount of extractable soil water in the profile was 119 mm at elongation and fell to 60 mm by the soft dough stage.

Stepwise regression analyses were employed to 1) identify the environmental parameters that were most important in determining crop response and 2) to develop prediction equations for the agronomic characters under investigation.

Evaporation in GS 3 was the singlemost important factor influencing grain yield (Table 1, equation 1a). This observation supports the findings of many other researchers who have previously identified the growth period between stem elongation and anthesis at the "critical" period for moisture sensitivity in wheat (Nix and Fitzpatrick, 1969; Fischer, 1973; Doorenbos and Kassam, 1979). The addition of root zone water (RZA) at anthesis increased the predictability of grain yield (equation 1b) indicating that a reasonable estimate of this agronomic parameter could be made based on environmental measurements up to the time of anthesis. It is known that cereal crops are most susceptible to stress during their most rapid development phase (Aspinall et al., 1964), which in wheat occurs around heading. The importance of post-anthesis stress should not, however, be overlooked. Significantly more variation was explained when E6 was included in equation 1c. Given the relatively large regression coefficient for E6 and the typically high evaporation rates prevailing at this time of year in regions with semi-arid climates like that of Saskatchewan, the potential impact of late season stress grain yield is obviously quite large.

Protein concentration was most dependent upon root zone water at elongation (RZE) (Table 1). The addition of E6 in equation 2b significantly improved the predictability of protein concentration suggesting that late season stress increases protein concentration. Based on the observation that soil water availability at elongation increased grain yield ($r=0.63^*$) and that increases in E6 decreased grain yield (equation 1c), it could be concluded that effects of both RZE and E6 on protein concentration were a function of the often reported inverse relationship between grain yield and protein concentration (Dubetz and Bole, 1973; Smike & Greb, 1973).

Evaporation in GS3 was the most important climatic factor determining protein yield (Table 1). This same factor accounted for most of the variability in grain yield, indicating a strong interdependence of grain and protein yield (Fowler et al. al., 1987). Addition of GDD4 to equation 3a significantly increased the predictability of protein yield.

Based on observations made in this study it was concluded that "critical" stress periods exist for winter wheat produced under no-till Saskatchewan. The most sensitive period for each of the agronomic parameters considered generally coincided with their most rapid development phase. The development period immediately prior to anthesis (GS3), which normally occurs between 9 June and 24 June for winter wheat produced in central Saskatchewan, was especially important in determining the expression of most characters. The importance of prevailing moisture conditions during this pre-anthesis period in the determination of grain yield supports much of the previous work reported in the literature. The suggestion by Robertson (1974) that pan evaporation is one of the best single weather elements for use as an indication of yield in the prairie region also received strong support from observations made in this study. Most of the variation in yield and grain protein could be explained by simple and inexpensive weather measurements. For example, precipitation and/or evaporation during critical periods explained 72% of grain yield and 82% of protein yield. In contrast, grain protein content was most dependent upon extractable soil water in the rooting zone. Grain yield and protein yield predictability were improved with the addition of soil water measurements.

2. Nitrogen fertilizer effect on crop productivity.

Over the 7 locations and 2 water regimes, N fertilization increased pre-anthesis crop water use by an average of 7mm while dry matter production at anthesis (DWTA) was increased by an average of 1150 kg/ha (Table 2). Nitrogen additions also resulted in a significantly higher water use efficiency (WUE) of pre-anthesis dry matter production. Greater WUE associated with higher early season dry matter production likely occurred because the soil water was transpired through the plant and not lost by direct soil evaporation (Fischer and Turner, 1978). French and Schultz (1984) reviewed water use at 61 dryland locations in S. Australia and concluded that a higher WUE early in the season was important in maximizing wheat yield under water-limiting conditions. While efficient production of dry matter before anthesis is important to yield, overproduction of dry matter could lead to water shortages after anthesis (Fischer and Kohn, 1966). For example, while N fertilizer additions generally increased the number of tillers at the elongation stage, a higher percentage of these tillers did not form heads (only measured out two locations) (Figure 1). Whether or not higher tiller mortality is wasteful is still being debated. Shanahan et al. (1984) suggested that the number of tillers which survive to form heads, and not initial production, is most important to final yield.

Measurements at crop maturity indicated that N additions significantly increased tiller density (Table 3). Therefore, despite higher tiller mortality, N additions increased the final density of this yield component. Total dry matter at maturity, grain yield, WUE of grain yield and grain protein content were also significantly increased by N. Therefore,even though N caused greater soil water use before anthesis (much greater in some instances), which resulted in less available water for grain filling, no yield decline due to added N was ever recorded. Passioura (1977) suggested that as long as 30% of total water use is available for grain filling, no decline in grain yield should occur. In our experiment an average of 40% of total water available was available after anthesis. Therefore, based on our results it could be concluded that the importance of N to grain resulted from more efficient water utilization, especially early in the growing season when dry matter accumulation is greatest.

3. Cultivar effect on crop productivity.

The tall cultivar 'Norstar' and the semi-dwarf cultivar 'Norwin' were compared under dryland conditions at 6 locations between 1984 and 1986. Results of the performance of these two cultivars in a range of environments indicated that they responded differently to different conditions. When the sites were analyzed separately based on the degree of pre-anthesis pan evaporation (Figure 2) it was clear that Norstar outperformed Norwin under stress conditions while the opposite was true under non-stress conditions. Under high stress, Norstar had a significantly higher DWTA and a significantly higher grain yield (Table 4). Under low stress conditions, Norstar again produced significantly higher amounts of dry matter, however, Norwin yielded higher than the tall cultivar (N.S.). In this low stress environment, Norwin also had a significantly greater WUE and HI. These observations indicated that under excellent growing conditions the semi-dwarf was more efficient in dry matter production per unit of water used and more efficient in terms of grain yield production per unit of dry matter production.

Based on these observations it was suggested that Norstar is best adapted to conditions of high to medium stress (grain yields of approximately 1300 to 3000 kg/ha) while Norwin is best adapted to high productivity environments (yields greater than 4000 kg/ha).

SUMMARY AND CONCLUSIONS

Based on observations made in these experiments, it was concluded that the pre-anthesis crop moisture environment is extremely critical in determining winter wheat productivity in Saskatchewan. Nitrogen fertilization was found to significantly affect both crop water use and water use efficiency during the pre-anthesis period. The response to N was positive. Even under very dry conditions, N fertilization increased grain yields. It was suggested that greater efficiency of water use with N fertilization was the result of increased transpiration of water through the plant (i.e.: more transpiration vs. soil evaporation), especially before anthesis.

The pre-anthesis moisture environment was also important in determining the relative performance of tall and semi-dwarf cultivars. Norstar appeared better adapted to dry conditions because of its ability to assimilate dry matter more rapidly. Our results would generally support the concept that higher wheat yields are obtained with higher pre-anthesis water use and higher dry matter production (Innes and Blackwell, 1981; Steiner et al., 1985). However, under favourable conditions, production of a semi-dwarf cultivar such as Norwin resulted in higher efficiency of pre-anthesis available water (ie:a higher WUE of DWTA) and greater production of grain per unit of dry matter.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support by E.R.D.A. The expert technical assistance by K.J. Greer is also acknowledged.

Table 1. Regression of several climatic and soil water variables on grain yield and grain protein.

Dependent Variable	Equation Number	Regression Equation	R
Grain	1a	Y = 8506-E3 (56.6)	0.72**
yield	1b	Y = 6969-E3 (50.2)+RZA(13.2)	0.81**
kg/ha	1c	Y = 8613-E3(29.3)+RZA(16.1)-E6(39.4)	0.91**
Grain	2a	Y = 17.4-RZE (0.61)	0.54**
protein	2b	Y = 10.7-RZE (0.50) +E6 (0.06)	0.73**
Protein	3a	Y = 992.6-E3 (6.28)	0.71**
yield	3b	Y = 509.2-E3 (5.48) +GDD4 (2.11)	0.82**
kg/ha			

*,** Significant at 0.05 and 0.01 probability levels, respectively.

Table 2. Influence of N rate on crop growth, water use and water use efficiency; mean of 7 locations and 2 moisture regimes.

N Rate kg/ha	Dry matter at anthesis kg/ha	Water use to anthesis mm	WUE of dry matter at anthesis kg/ha/mm
0	2948 b	145 b	21.8 b
33	3916 a	150 ab	28.1 a
67	4232 a	155 a	28.9 a
100	4147 a	151 a	29.4a

Numbers in a column followed by different letters are significantly different (P<0.05).

Table 3. Influence of N on growth, grain yield and protein and water use efficiency; mean of 7 locations and 2 moisture regimes.

N rate kg/ha	Heads sq. m.	Total dry matter kg/ha	Grain yield kg/ha	WUE grain kg/ha/mm	Grain protein %
0	400 b	7346 b	2204 b	8.0 b	10.5 c
33	450 a	9103 a	2578 a	9.4 a	10.6 c
67	433 a	8731 a	2624 a	9.5 a	11.1 b
100	440 a	8918 a	2528 a	9.1 a	11.7 a

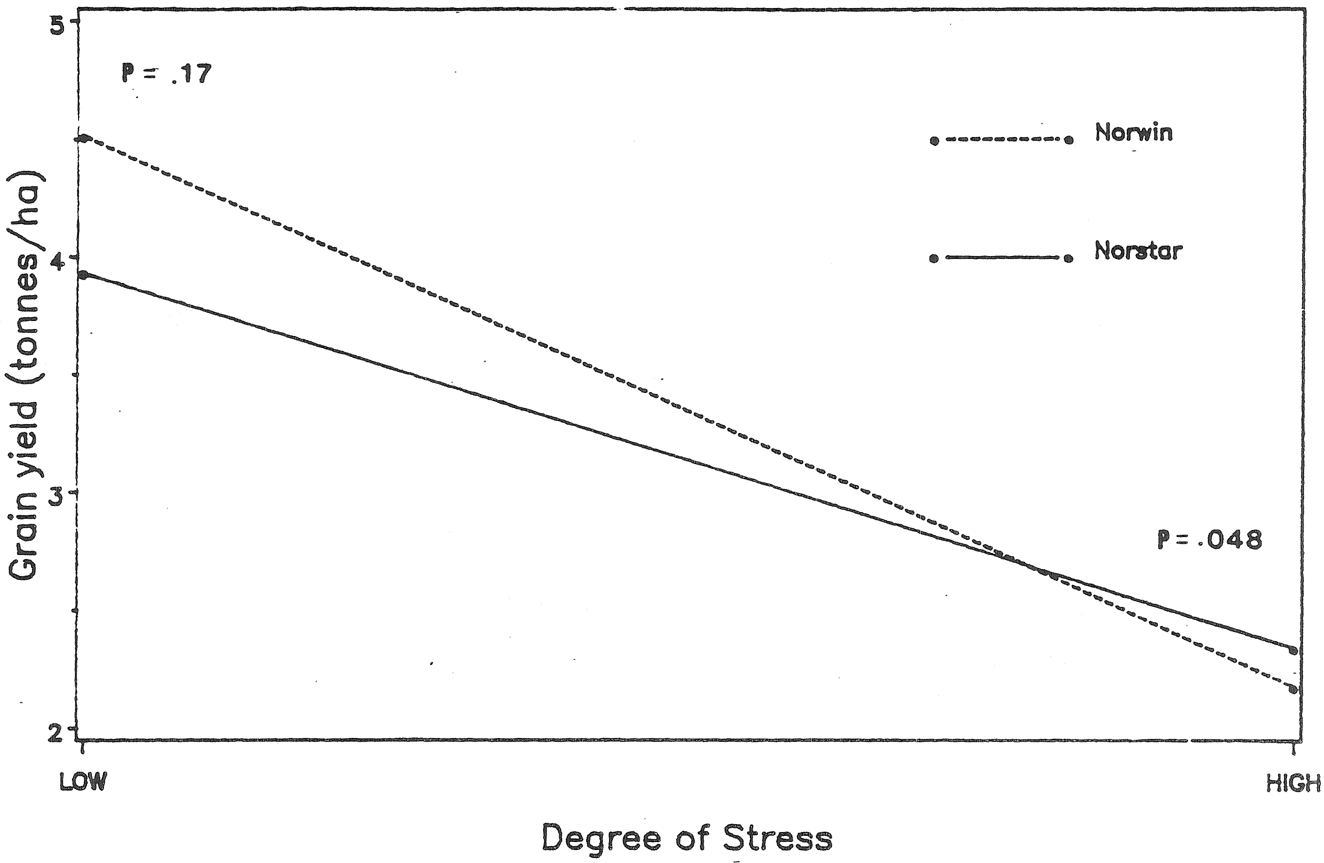
Numbers in the same column followed by different letters are significantly different ($P<0.05$).

Table 4. Productivity of two genotypes under high and low stress conditions; 6 locations.

Genotype	Dry matter anthesis kg/ha	Dry matter maturity kg/ha	Grain yield kg/ha	Water use mm	Grain WUE kg/ha/mm	Harvest index
		- - - - - - high stress - - - - -				
Norstar	3922 a	7248 a	2339 a	262 a	9.0 a	0.33 a
Norwin	3439 b	6974 a	2174 b	260 a	8.5 a	0.32 a
		- - - - - low stress - - - - -				
Norstar	4982 a	14419 a	3929 a	283 a	14.0 b	0.27 b
Norwin	4389 b	12717 b	4510 a	278 a	16.2 a	0.36 a

high stress: 247 mm evaporation during 30 days pre-anthesis
low stress: 157 mm evaporation during 30 days pre-anthesis

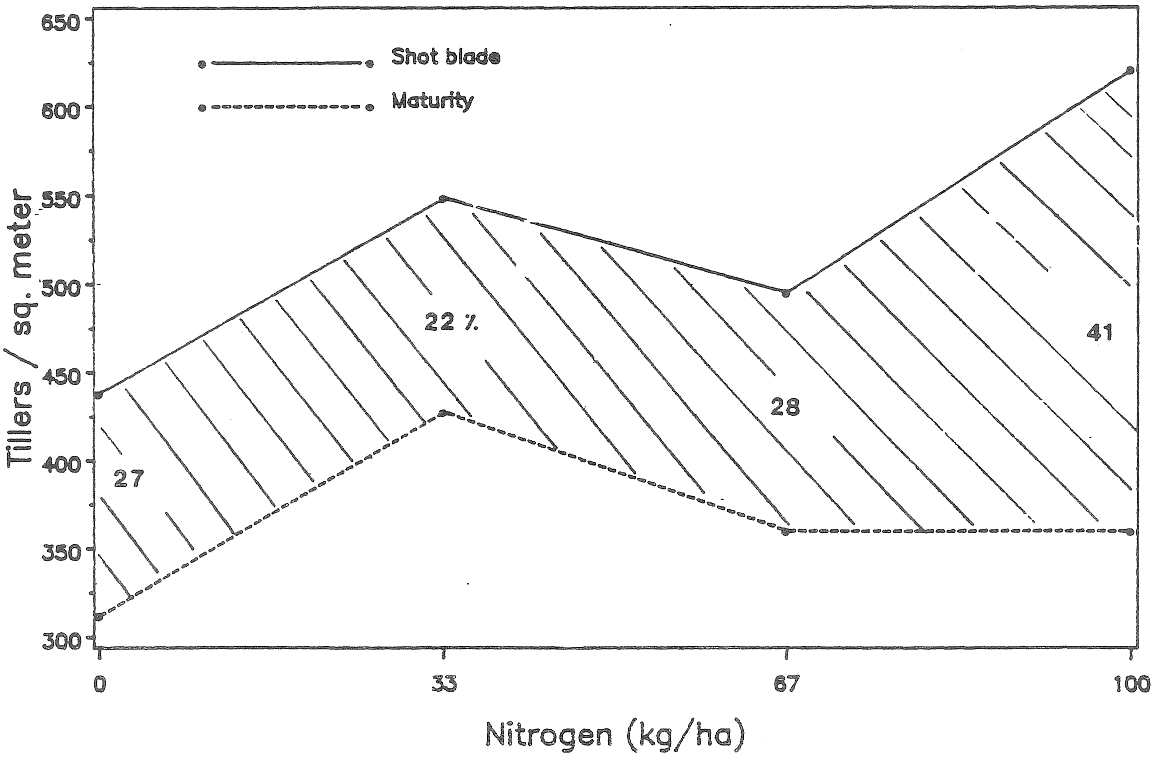
numbers in the same column followed by different letters are significantly different ($P<0.05$)



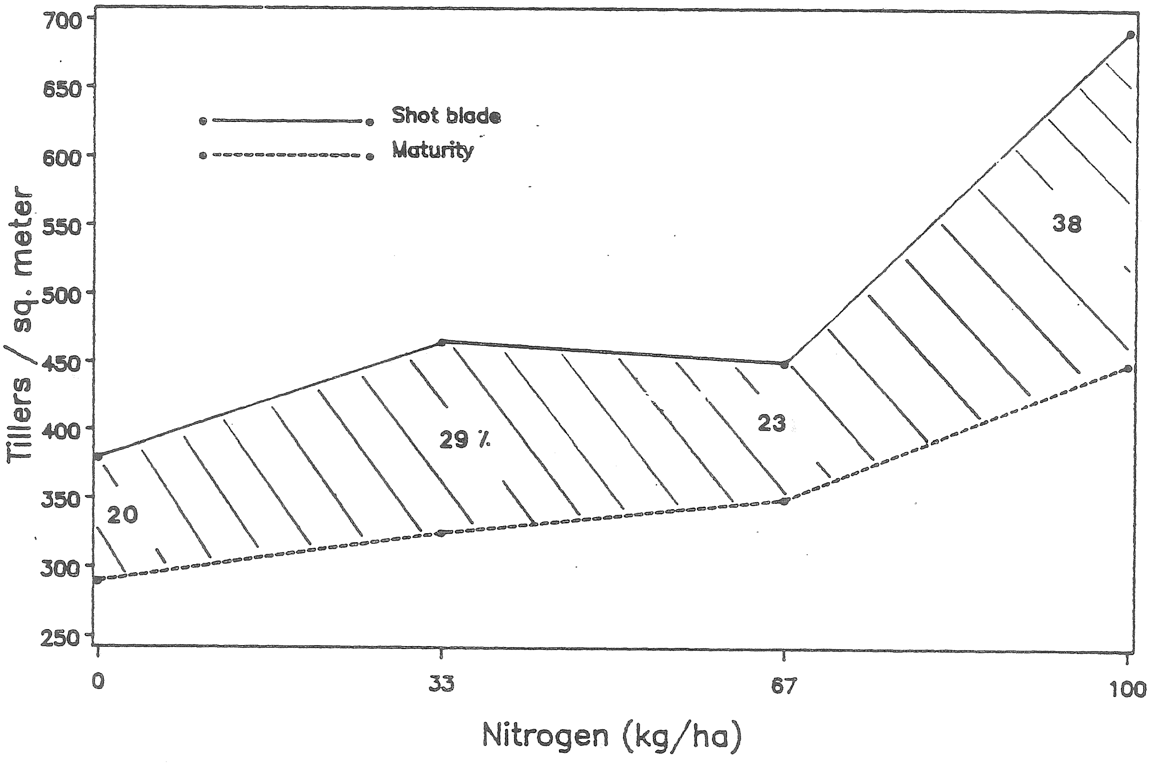
Two genotypes under low and high pre-anthesis moisture stress
6 locations combined, 1984-1986, Saskatchewan, Canada

figure 2

figure 1



Tillers/sq. meter at shot blade, and spikes/sq. meter at maturity: Outlook, 1986, Saskatchewan, Canada



Tillers/sq. meter at shot blade, and spikes/sq. meter at maturity: Clair, 1986, Saskatchewan, Canada

REFERENCES

Aspinall, P., D.B. Nichols and L.H. May. 1964. The effects of soil moisture stress on the growth of barley. Aust. J. Agric. Res. 15: 729-745.

Briggle, L.W. and O.A. Vogel. 1968. Breeding short stature, disease resistant wheats in the United States. Euphytica 17, Suppl.I: 107-130.

Brown, P.L. 1971. Water use and soil water depletion by dryland winter wheat as affected by nitrogen fertilization. Agron. J. 63: 43-46.

Doorenbos, J. and A.H. Kassam. 1979. Yield response to water. FAO publications no.33. pp. 164-170.

Dubetz, S. and J.B. Bole. 1973. Effects of moisture stress at early heading and of nitrogen fertilizer on three spring wheat cultivars. Can. J. Plant Sci. 53: 1-5.

Entz, M.H., K.G. Gross, D.B. Fowler, E. de Jong and K.J. Greer. 1987. Influences of nitrogen fertilization on winter wheat rooting patterns and soil water extraction. p. 306-328. In Proc.: 1987 Soils and Crops Workshop. Ext. Div. Univ. Sask., Saskatoon, Can.

Fischer, R.A. 1973. The effect of water stress at various stages of development on yield processes in wheat. p. 233-241. In R.D. Slaytner (ed.) Plant response to climatic factors. Proc. Uppsala Sym. 1970, Unesco, Paris.

Fischer, R.A. and G.D. Kohn. 1966. The relationship of grain yield to vegetative growth and post-flowering leaf area in the wheat crop under conditions of limited soil moisture. Aust. J. Agric. Res. 17: 281-295.

Fischer, R.A. and N.C. Turner. 1978. Plant productivity in the air and semi-arid zones. Ann. Rev. Plant Physiol. 29: 277-317.

Fowler, D.B., J. Brydon and R.J. Baker. 1987. Optimizing nitrogen fertilizer response by winter wheat and fall rye. p. 361-376. In Proc.: 1987 Soils and Crops Workshop. Ext. Div. Univ. Sask., Saskatoon, Can.

Fowler, D.B. and M.H. Entz. 1986. Role of winter wheat in tillage systems. p. 147-172. In Proc.: Tillage and Soil Conservation symposium. Agric. Can., Indian Head Exp. Farm, Indian Head, Sask., Can.

French, R.J. and J.E. Schultz. 1984. Water use efficiency of wheat in a Mediterranean-type climate. I. The relation between yield, water use and climate. Aust. J. Agric. Res. 35: 743-764.

Henry, J.L., J.B. Bole and R.C. McKenzie. 1987. Effect of nitrogen water interactions on yield and quality of wheat in western Canada. p. 165-191. IN A.E. Slinkard and D.B. Fowler (eds). Wheat production in Canada: a review. Div. Ext. Univ. Sask., Saskatoon, Can.

Innes, P. and R.D. Blackwell. 1981. The effect of drought on the water use and yield of two spring wheat genotypes. J. Agric. Sci. 96: 603-610.

Laing, D.R. and R.A. Fischer. 1977. Adaptation of semi-dwarf cultivars to semi-dwarf conditions. Euphytica 26: 129-139.

Lehane, J.J. and W.J. Staple. 1965. Influence of soil texture, depth of soil moisture storage and rainfall distribution on wheat yield in southwestern Saskatchewan. Can. J. Soil Sci. 45: 207-219.

Nix, H.A. and E.A. Fitzpatrick. 1969. An index of crop water stress related to wheat and grain sorghum yields. Agr. Meteorol. 6: 321-337.

Passioura, J.B. 1977. Grain yield, harvest index an water use of wheat. J. Aust. Inst. Agric. Sci. 43: 117-120.

Robertson, G.W. 1974. Wheat yields for 50 years at Swift Current, Saskatchewan in relation to weather. Can. J. Plant Sci. 54: 625-650.

Ritchie, J.T. 1983. Climate and soil water p. 1-23. In. M. Stelly et al. (ed.). Moving up the yield curve: advances and obstacles. Spec. Publ. 39. American Society of Agronomy, Soil Science Society of America, Madison, WI.

Shanahan, J.F., K.J. Donnelly, D.H. Smith and D.E. Smika. 1984. Shoot development properties associated with grain yield in winter wheat. Crop Sci. 25: 770-775.

Singh, S.D. 1981. Moisture-sensitive growth stages of dwarf wheat and optimal sequencing of evapotranspiration deficits. Agron. J. 73: 387-391.

Smika, D.E. and B.W. Greb. 1973. Protein content of winter wheat grain as related to soil and climatic factors in the semi-arid central great plains. Agron. J. 65: 433-436.

Steiner, J.L., R.C.G. Smith, W.S. Meyer and J.A. Adeney. 1985. Water use, foliage temperature and yield of irrigated wheat in south-eastern Australia. Aust. J. Agric. Res. 36: 1-11.

Terman, G.L. 1979. Yields and protein content of wheat grain as affected by cultivar, N and environmental growth factors. Agron. J. 71: 437-440.

Viets, F.G. 1966. Increasing water use efficiency by soil management. p. 259-274. In W.H. Pierre et al. (eds.) Plant environment and efficient water use. Am. Soc. of Agron. and Soil Sci. Soc. of Am. Madison, WI.